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# Novel type of avalanche photodetector with Geiger mode operation

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**Abstract**

A novel type of avalanche photodetector with Geiger mode operation, known as Silicon Photomultiplier (SiPM) is presented. Development of photodetectors for the detection of low intensity photon flux is one of the critical issues for experimental physics, medical tomography and many others. The structure of the photodetector is based on metal–resistor semiconductor (MRS) microcells with a density of $1000/mm^2$, operating in the Geiger mode with an internal amplification gain of $10^5$–$10^6$, with a photon detection efficiency of 32% for light in the green band of the visible spectrum, and a time resolution of about 30 ps. The structure of the photodetector gives the possibility of detecting a low flux of up to 1000 photoelectrons with proportional output. A Novel type of silicon photomultiplier is currently being tested for the TESLA scintillation tile hadron calorimeter.


*Keywords:* Silicon avalanche photodetector; Single photon mode operation

## 1. Introduction

The silicon avalanche photodetector with Geiger mode operation—silicon photomultiplier (SiPM) is a combination of microcell semiconductor structure with integrated quenching mechanizm and common electrode structure. The silicon avalanche microcells with very low noise currents are operated in the Geiger mode, in which the bias voltage is above the diode breakdown voltage. In this mode, any electron event in the sensitive area will produce a very large current flow with amplification gain of up to $10^6$. In this case single photon counting mode can be realized, in that, single photon events can be detected from the minimum count rate allowed by the background noise count.

All microcells are identical, independent and operated in single photon counting mode. The common electrode structure and quenching mechanism based on a specially resistive material technology gives the possibility to act as proportional detector for the measurement of low intensity photon flux. The output signal is defined as sum of the Geiger mode signals of microcells triggered by initial flux of photons.

The typical density of microcells, can be produced, is 1000–5000 per $mm^2$ and the total number of microcells on the tested photodetector with sensitive area 1 $mm^2$ is 2000. This is define by the dynamic range of the photodetector.

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The noise conditions of the SiPM is defined by dark count rate, as in Geiger mode operation a single thermally generated electron or hole can initiate an avalanche, leading to an electrical pulse that is indistinguishable from a single photon detection. This gives the main limitation of increasing the sensitive area of SiPM operated in single photon counting mode, but it is not so significant for low photon flux measurement, $N_{phot} > 5$.

## 2. Structure of the SiPM, principle of operation and optimization

### 2.1. Structure of the SiPM

The structure of the silicon photomultiplier is a combination of large number of avalanche microcells on a single substrate and with common quenching mechanism (resistive layer) and common electrodes [1].

### 2.2. Structure of avalanche microcell

The schematic structure of avalanche microcell of SiPM is shown Fig. 1 and presents a well-known ‘‘reach through avalanche structure’’ [2].

A reach-through avalanche microcell is an avalanche structure $n^+$–p–π–$p^+$, where π represents very slight p-type doping. The $n^+$ side is thin and it is this side that is illuminated through a window.

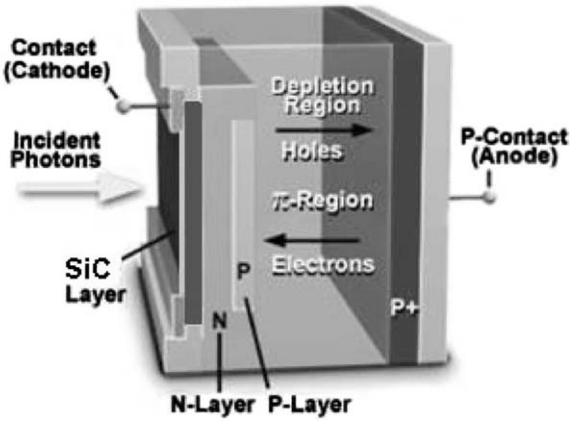


Fig. 1. Shematic vew of the SiPM microcell.

There are three p-type layers of different doping levels next to the $n^+$ layer to suitably modify the field distribution across the structure. The first is a thin p-type layer, the second is a thick lightly p-type doped (almost intrinsic) π-layer, and the third is a heavily doped $p^+$ layer. The diode is reverse biased to increase the fields in the depletion regions. Under reverse bias is applied, the depletion region in the p-layer widens to *reach-through* to the π-layer. The field extends from the exposed positively charged donors in the thin depletion layer in the $n^+$ side. The electric field is at a maximum at the $n^+$p junction, then decreases slowly through the p-layer. Through the π-layer it decreases only slightly as the net space charge density here is small. The field vanishes at the end of the narrow depletion layer in the $p^+$ side. The absorption of photons, and hence photogeneration, takes place mainly in the π-layer. The nearly uniform field here separates the electron–hole pairs and drifts them at velocities near saturation towards the $n^+$ and $p^+$ sides, respectively. When the drifting electrons reach the p-layer, they experience even greater fields and may be accelerated by the high fields to sufficiently large kinetic energies to further cause impact ionization and release more electron hole pairs which leads to an *avalanche of impact ionization processes*. Thus, from a single electron entering the p-layer, one can generate a large number of electron hole pairs all of which contribute to the observed photocurrent. The photodiode possesses an *internal gain mechanism* in that a single photon absorption leads to a large number of electron hole pairs generated.

The resistive layer on the top of the $n^+$ layer is an important feature of the avalanche microcell structure with Geiger mode operation and providing the negative feedback in the local area of multiplication (quenching mechanism). The avalanche process increases current through a resistive layer and a charge distribution accumulation on the resistive layer-silicon interface. The result of charge redistribution is a redistribution of the potential in the structure and an increasing electric field of opposite direction, which screens the initial electric field. The negative feedback produced causes a deceleration of the avalanche process and its termination. It is important to note that the resistive layer negative feedback is of local nature due to very low tangential conductivity of the resistive layer. The resistive layer on the silicon wafer can be made from various materials having a wide energy gap and suitable conductivity (for example SiC).

### *2.3. Quantum efficiency of SiPM and optimization of structure*

Quantum Efficiency (QE) of SiPM is a product of two factors: quantum efficiency and geometrical efficiency. The QE is the percentage of the number of photons incident on the photodetector which contribute to the output charge signal and depends on the absorption efficiency and triggering probability.

The QE of sensitive area of SiPM:

$$QE = \varepsilon_G(1 - R)(1 - e^{-\alpha x}),$$

where $\alpha$ is the coefficient of absorption, $R$ the reflection coefficient and $\varepsilon_G$ the geometrical efficiency.

The criteria of optimization is to provide the thickness of active area in order to maximize the useful absorption, but it is necessary to minimize the size of the multiplication region in order to reduce instabilities in the avalanche process due to excessive local electric fields (greater field uniformity may be obtained in a thin region) and creating a thermal electrons.

The fraction of light transmitted to the sensitive region is defined by technological layers of the top contact and resistive layers and was optimized for the green range of light (left edge of sensitive spectra). The absorption coefficient of light in Si depends on its wavelength $\lambda$. For $\lambda = 400\,\text{nm}$ (corresponding to photon energy $hv = 3.10\,\text{eV}$) the absorption coefficient is $= 5.4 \times 10^6\,\text{cm}^{-1}$. Therefore the shorter wavelength 450–550 nm, the thickness required to absorb 99.9% of the light is small $\sim 2.33\,\mu\kappa$. For optimization of sensitivity in green region of light the depletion region of $5\,\mu\kappa$ was chosen which gives the possibility to use the low resistive Si (right edge of sensitive spectra).

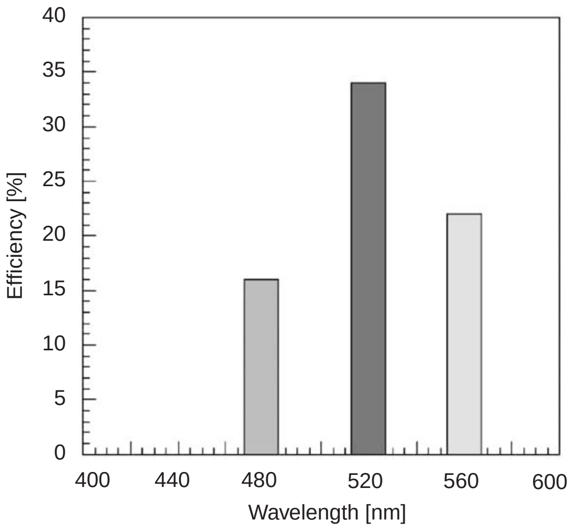

Fig. 2. Quantum Efficiency of the SiPM.

Geometrical efficiency is defined by technological process and topology of SiPM and equals $\sim 0.6$.

The total efficiency including geometrical efficiency of SiPM for optimized visible spectrum is shown in Fig 2.

### *2.4. Noise consideration (dark current rate)*

As mentioned early, in a Geiger mode microcell detection of an event does not give intensity information. The output pulse produced by the detection of a photon is indistinguishable from that produced by the detection of many simultaneously absorbed ones. That means a single thermally generated electron or hole can initiate an avalanche, leading to an electrical output pulse that is indistinguishable from a photon detection. For photon counting mode, such an events represent a false signal whose probability needs to be minimized. The number of dark current induced events per second is the dark count rate. The dark current mainly defined the thermally generated bulk current, curriers in the depleted region. For limitation of dark count rate the sensitive area of the SiPM is chosen as $1\,\text{mm}^2$ and with an optimized thickness of depleted region

Table 1
Main characteristics of the SiPM

| Par. | Value |
|---|---|
| Sensitive area | 1 mm$^2$ |
| Number of microcells | 2000 |
| Amplification gain | $10^5$–$10^6$ |
| Bias voltage | 50 *V* |
| Efficiency (green light) | 34% |
| Fast timing | 30 ps |
| Magnetic field sensitivity | no |

of the SiPM the total dark count rate of photodetector structure, on the level of single photoelectron is 400 kHz.

### 2.5. Characteristics of SiPM

Finally, the main characteristics of Si PM are shown in Table 1.

## 3. Applications: SiPM for tile Hadron calorimeter of TESLA

We have studied the possibility of a tile scintillator and a WLS fiber readout with an Si Photomultiplier, for the Tesla Hadron Tile Calorimeter [3]. The plastic scintillation tile with a wavelength shifter (WLS) readout has become widely used in modern calorimeter systems, because of the need to readout a very large number of tiles in the small space available and in conditions with a high magnetic field up to 4 T.

In order to demonstrate the feasibility of TESLA hadron calorimeter, calibration by a minimum ionising particles (*mip*) with the scintillation tile equipped by SiPM the test measurements were performed.

The main requirements of the photodetectors for TESLA hadron calorimeter are the possibility to detect the low intensity flux of photons for calibration purposes and a wide dynamic range of photodetectors as determined by [4]:

- minimal signal: *mip*—muons, proposed for calibration purposes and expected light yeld is ~85 photons on the photodetector plain and
- maximal signal: high-energy jet, the expected number of photons is ~2500 on the photodetector plain.

The sensitive element is 5 × 5 cm and 5 mm thick scintillation tile (Bicron BC-408) with WLS readout fiber (Kuraray Y11) of 1 mm in diameter which can be coupled with clear fiber for transmission of the light to photo detector. The two loops of the WLS fiber where embedded in a plastic body, without covering the free end of the fiber by mirrors, the other one was connected to the SiPM.

Figs. 3 and 4 shows the test beam test results with relativistic pions.

In Fig. 3 represents the spectrum of low flux photons, detected by SiPM. The spectrum shows the pedestal of photodetector and single photon spectrum mode with peaks 1–3 photons. One significant feature of SiPM can be mentioned, such spectrum gives a method of absolute calibration of the readout of scintillation tiles.

In Fig. 4 represents the spectrum of *mip* signal with mean value of number of photoelectrons is 12.93.

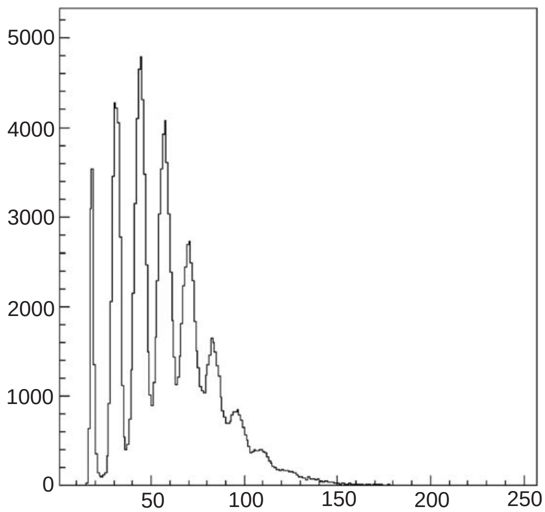


Fig 3. Low photons flux detected by SiPM.

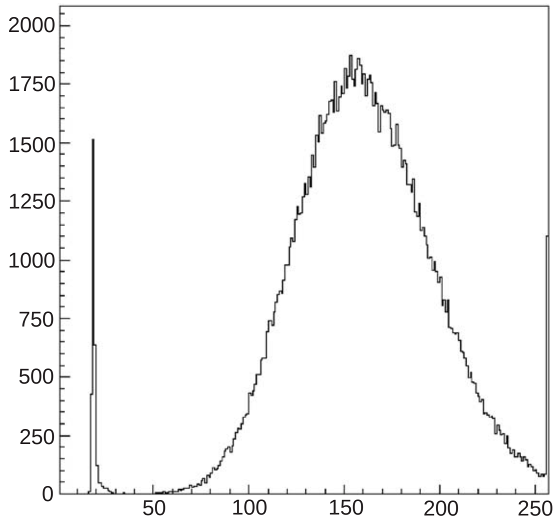


Fig 4. Signal of *mip*, detected by SiPM.

## 4. Conclusion

The design and technology of production of novel type of Silicon avalanche photodetectors with Geiger mode operation (SiPM) exists and latest test measurements have shown stable results. SiPM characteristics are already fit well to the requirements of the operation in the TESLA hadron sctintillation tile calorimeter system with strong magnetic field and includes the possibility of calibration with *mip* signal.

Novel types of the avalanche photodetectors could be interesting for applications in positron emission tomography (PET) for stintillation detector system.

## Acknowledgements

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